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Carbon dynamics in surface and deep soil in response to increasing litter addition rates in an agro-ecosystem

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ABSTRACT

Increasing atmospheric CO_2 concentration and nitrogen deposition are predicted to increase fresh carbon (C) inputs in soils because of higher net primary productivity. However, relationship between soil C cycling and increased inputs of fresh C in soils is not clear. Moreover, most of the studies on soil organic carbon (SOC) focus on upper 20 cm although > 50% SOC is present below this depth. We designed this study to unravel the response of SOC to 0% (control), 0.3%, 0.6%, 1.2% and 2.4% addition of maize litter (C4) to a surface (0–15 cm) and deep layers (55–75 cm) of a C3 soil. The isotopic difference between the maize litter and soil allowed distinguishing soil-derived (native) CO_2-C from litter-derived CO_2-C and calculating the priming effect (PE). Total respiration was measured over 78 d incubation whereas the PE was determined 39 d and 78 d after incubation. Our results showed that all the litter addition levels induced PE -stimulation of mineralization of the extant SOC in response to availability of fresh organic matter (FOM)- in surface and deep soil layers. Moreover, the PE was significantly higher in the deep than surface soil layer in response to all litter additions, except 2.4% treatment during the 2nd harvest. This result suggests that the deep SOC would mineralize at higher rates under similar supply of FOM to surface and deep soils in this agroecosystem. We also showed a significantly positive linear relationship between PE and litter addition rates for both soils implying continuous loss of SOC under increasing organic matter inputs. In conclusion, our study reveals that the deep soil C would be more vulnerable to priming effect in response to litter addition than the surface soil.

1. Introduction

Soil organic matter mineralization represents one of the largest fluxes in the global C cycle (Kirschbaum, 2000; Schlesinger and Andrews, 2000). A small increase in its rate in response to global changes can significantly increase the atmospheric CO_2 pool thereby causing a positive feedback to global warming (Bond-Lamberty and Thomson, 2010). Despite this importance, controls on mineralization of SOC are poorly understood (Schmidt et al., 2011; Shahzad, 2012). Moreover, SOC dynamics in deep soil layers are even less clear than the surface C despite that > 50% of SOC is stored below 20 cm (Jobbágy and Jackson, 2000).

A change in rate of SOC mineralization in response to additions of fresh organic matter (FOM) i.e. root exudates, rhizodeposition or litter is termed as priming effect (PE) of SOC (Bingeman et al., 1953; Fontaine et al., 2003; Kuzyakov et al., 2000). It is a common phenomenon in ecosystems and potentially a large soil C pool is under the influence of the PE (Dijkstra et al., 2009; Shahzad, 2012). The most plausible mechanisms of priming include an acceleration in SOC mineralization after addition of organic matter and the co-metabolism of fresh and old organic matter by soil microorganisms (Finzi et al., 2015; Fontaine et al., 2003; Kuzyakov, 2010; Zhang et al., 2013). Although known since long, the importance of SOC priming for ecosystem functioning has been recognized recently, consequently leading to its

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inclusion in soil organic matter cycling models (Bingeman et al., 1953; Cheng et al., 2014; Drake et al., 2011; Finzi et al., 2015; Fontaine and Barot, 2005; Perveen et al., 2014). However, the occurrence and the importance of the PE in deep soils has been poorly studied.

Global changes like elevated atmospheric CO_2, N deposition etc. are expected to raise the net primary productivity thereby leading to higher inputs of plant C into soils (Hyvönen et al., 2007; Uselman et al., 2000). The higher inputs should intuitively lead to higher SOC stocks. However, it is not always the case under experimental conditions. For instance, negative SOC budgets were found despite higher productivity over multiple years of experimental exposure of plants to elevated CO_2 (Carney et al., 2007; Van Groenigen et al., 2014; Langley et al., 2009). This counter intuitive decrease in soil C stocks, attributed to PE, means that the mineralization of the extant SOC surpasses the new C that is being stabilized. This phenomenon, therefore, begs the questions: what is the relationship between rates of C inputs and mineralization of extant SOC? Is there a saturation point where the microorganisms, upon FOM availability, downregulate or stop mineralization of extant SOC? Alternatively, does the PE has a positive relationship with FOM input rates?

A few studies have explored these questions in surface soils and reported contradictory results. For example, priming effect was proportional to the amounts of added FOM (i.e. root mucilage, litter and glucose) in a study (Mary et al., 1993). For different rates of litter addition, positive but non-linear rates of PE have been reported whereby PE per unit of added litter decreased with increasing litter inputs (Guenet et al., 2010; Xiao et al., 2015). Guenet et al. (2010) argued that the PE is a saturating function of FOM inputs. On the contrary, plant biomass –as a proxy of plant C inputs in soils- was found in linear relationship with priming effect (Dijkstra et al., 2006; Shahzad et al., 2015). Thus, the question of a relationship between FOM availability and priming effect is unclear so far.

Persistence of deep SOC for centuries to millennia, discovered thanks to ^{14}C dating (Jenkinson et al., 2008; Trumbore, 2000), prompted proposals to incorporate FOM mechanically or through development of deep rooting plants for long term sequestration of atmospheric CO_2 in deep soils (Kell, 2011; Lorenz et al., 2011; Lorenz and Lal, 2005). The implicit assumption in these proposals is that the increased delivery of FOM in deep soil layers would sequester the added C for long term owing to an insignificant microbial decomposition. However, recent studies have revealed that addition of FOM to deep soils induce strong priming of deep SOC (Bernal et al., 2016; Fontaine et al., 2007; Shahzad, 2012; Wordell-Dietrich et al., 2017). Supply of FOM in lab incubations or through living roots in soil-plant systems have been found to induce mineralization of millennia old deep SOC (Fontaine et al., 2007; Shahzad, 2012). These studies indicate that the deep SOC can mineralize at higher rates if energy rich FOM is available to deep soil microorganisms. Therefore, the increase in deep soil C stocks after increasing the FOM inputs is not a given thereby warranting the research on FOM input rates and the amount of PE in deep soils.

We designed this study to determine the response of surface (0–15 cm) and deep soil C (55–75 cm) to varying amounts of FOM (maize litter) in a semi-arid agroecosystem. We hypothesized that litter amendment would induce priming effect in both soil depths. Moreover, we expected that the PE would be more important in deep than surface soil. We used senesced C4-maize leaves and a C3 soil to use the $\delta^{13}C$ isotopic difference between the two sources of CO_2 efflux for calculating priming effect.

2. Materials and methods

2.1. Soil sampling and preparation

An Aridisol soil was sampled from 0 to 15 cm and 55–75 cm depth intervals from Wheat Research Station, Ayub Agriculture Research Institute, Faisalabad, Pakistan (31°23′41″N, 73°3′0″E). Soil texture in upper 15 cm is sandy clay loam whereas it is sandy loam at 55–75 cm depth. The sampled plot has been under wheat–fallow rotation for > 12 years and irrigation agriculture is practiced. Since most of the wheat root system remained confined to upper 0–15 cm, we decided the first sampling interval as 0–15 cm while the deeper interval of 20 cm at 55–75 cm depth. Soil was sampled from five different randomly spaced locations of the plot using an auger (internal diameter 4.8 cm) at the selected depths and a composite sample was made for each soil depth. All the dead or live roots and plant debris were removed from the soil. The individual soil samples from each depth were then sieved through a 2 mm mesh and resultant samples were mixed thoroughly to form a homogenized bulk sample for corresponding soil depth. Soil pH was measured in 1:5 (soil: water, w/v) suspensions using a pre-calibrated pH meter. It was 8.32 ± 0.02 and 8.29 ± 0.02 for 0–15 cm and 55–75 cm soils respectively. The initial SOC was determined using Walkley–Black method, consequently it was called WB-TOC (Walkley and Black, 1934). Water holding capacity (WHC) of the soil samples from each sampling depth was measured using the method of Jarrell et al. (1999). Initial physico-chemical properties of the soils are given in the Table 1.

Table 1
Physiochemical characteristics of soil & litter used for incubation.

Parameter	Surface soil (0–15 cm)	Deep soil (55–75 cm)	Maize litter
Sand (%)	53.7	51.28	
Silt (%)	21.05	19.22	
Clay (%)	25.25	29.5	
Textural class	Sandy clay loam	Sandy loam	
pH	8.32 ± 0.02	8.29 ± 0.02	9.01 ± 0.08
OC (g kg^{-1})	6.57 ± 0.43	3.49 ± 0.06	267.6 ± 11.2
Total N (g kg^{-1})	0.52 ± 0.04	0.41 ± 0.07	12.5 ± 1.7
C/N	12.6	8.51	21
$\delta^{13}C$ (‰)	−25.01 ± 0.2	−24.55 ± 0.1	−11.8 ± 0.1
WHC (%)	31.7 ± 1.2	33.3 ± 2.5	

Eighty grams dry-equivalent of a soil sample were placed in a 100-ml beaker. All these soil samples were placed in air tight mason jars and pre-conditioned by incubating them at 60% of WHC in an incubator at 25 °C for 2 weeks before the start of the experiment. Distilled water was used to maintain the required moisture content in the soils.

2.2. Litter characteristics

Senescent maize leaves were collected from another agriculture field of the study location, dried in an oven at 50 °C for 3 days and crushed to pass through a 1 mm sieve. Its C, N and $\delta^{13}C$ are given in the Table 1.

2.3. Soil incubation and analyses

After pre-incubation, soils were amended with four rates of ground-maize litter. The treatments included addition of maize C at the rate of 0.3% (3 g litter kg^{-1} dry soil), 0.6% (6 g litter kg^{-1} dry soil), 1.2% (12 g litter kg^{-1} dry soil) and 2.4% (24 g litter kg^{-1} dry soil), whereas un-amended soils were used as control. The ground litter was thoroughly mixed in the soils. With five levels of treatments and three replicates, number of samples for each soil were 15. The experiment consisted of two sets of microcosm units, out of which one was harvested midway on 39th day of incubation, whereas the second set was harvested at the end (78th day) of incubation. The amended and un-amended soils in beakers were placed in air- tight mason jars. In each mason jar, two glass vials, one containing 20 ml of 1 N NaOH to trap soil-released CO_2 and the other with 10 ml distilled water to avoid soil dryness, were placed. Jars for blanks contained the glass vials of NaOH and distilled water only. The jars were sealed with air-tight caps and incubated at 25 °C in the dark.

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